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Effects of Brownian motion and thermophoresis on nanofluids in a rotating circular groove: A numerical simulation

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ABSTRACT

We present a numerical study of the movement of nanoparticles (Cu) and heat transfer of nanofluids with Newtonian and non-Newtonian base fluids in this paper. The computing domain is a circular groove with a fixed slow speed of revolution. Two kinds of models with different definitions of thermal conductivity and concentrations of nanoparticles are considered in the numerical calculation process, as are the influences of thermophoresis and Brownian motion. A continuous finite element scheme in space and a modified midpoint scheme in time are used, and numerical solutions are obtained by using the finite element method. Compared with base fluids only, the heat transfer enhancement of nanofluids can be found easily and is more intuitive. The correlation of the heat transfer enhancement and power law index of base fluids used to distinguish different power law fluids is investigated. This contributes to determining the reasons for heat transfer enhancement in nanofluids. It is found that the Maxwell Model has a higher enhancement of heat transfer than the Traditional Model and the thermophoresis effect breaks the dynamic equilibrium of nanoparticles in the rotating circular groove.

1. Introduction

In recent years, the study of the flow, heat and mass transfer of nanofluids has been a topic of extensive research owing to its enhanced thermal conductivity [1]. Nanofluids consist of nanoparticles (such as copper Cu, silver Ag, iron oxide Fe_3O_4, alumina oxide Al_2O_3, copper oxide CuO, titanium oxide TiO_2, carbon nanotube CNT) with sizes of 1–100 nm suspended in base fluids (such as water, carboxymethyl cellulose CMC, alcohol and industry oil). Nanofluids have drawn wide attention owing to recently reported claims of high performance in heat transfer [2].

As increasing attention is paid to the application of nanofluids, a significant amount of research into the physical properties of nanofluids has been conducted and has helped to better explain the basic mechanism of nanofluids. For example, the suspensions of nanometer-sized particles and their spreading and adhesion behavior on solid surfaces can yield materials with desirable structural and optical properties [3]. Nanofluids with surfactant micelles can remedy soiling, remove oily soil, enhance oil recovery, and also improve the efficiency of oil recovery [4]. With an impressive enhancement in heat transfer properties, nanofluids are used to cool equipment and inkjets [5,6]. Thus, nanofluids have a wide range of applications in many fields such as energy, power, aerospace, aviation, vehicles, and electronics.

Choi [7] was the first to use the term “nanofluids” to refer to fluids with suspended nanoparticles. The thermal conductivity of base fluids improves greatly after nanoparticles are added. In the beginning, the volume fraction, shape, nanoparticle size, nanoparticle structure, microscopic motion, concentration, and dispersion were regarded as factors for the enhancement of the heat transfer of nanofluids [8–12]. Xuan and Li [8] showed that the volume fraction, shape, dimensions, and properties of the nanoparticles affect the thermal conductivity of nanofluids. Wang and Xu [13] measured the effective thermal conductivity of mixtures of fluids and nanometer-size particles by using a steady-state parallel-plate method. However, like Maxwell’s equation, the predicted theoretical thermal conductivities of nanoparticle-fluid mixtures were much lower than the experimentally measured data. This is presumably because these theoretical models did not consider the structure-dependent characteristics and microscopic movements these errors.

In 2006, Buongiorno [14] presented a new analytical model for convective transport in nanofluids considering Brownian motion and thermophoresis. In addition, he showed that Brownian motion and thermophoresis are the most important nanoparticle/base-fluid slip mechanics. Later, Kuznetsov and Nield [15] presented a

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Nomenclature

$\mathbf{x} = (x, y)$	the Cartesian coordinate system
$\mathbf{u} = (u_x, u_y)$	velocity of nanofluids
$\mathbf{U}$	dimensionless velocity of nanofluids
m	power-law index of the base fluids
t	time
t^*	dimensionless time
p	hydrostatic pressure
p^*	dimensionless pressure
T	temperature
T_w	temperature of the groove's wall
T_{inside}	initial inside temperature
C	concentration of nanoparticles
C_∞	characteristic concentration
V	characteristic velocity
L	radius of circular groove (characteristic length)
c_f	specific heat of base fluids
c_p	specific heat of nanoparticles
k	thermal conductivity of nanofluid
k_f	thermal conductivity of base fluids
k_p	thermal conductivity of nanoparticles
D_B	Brownian diffusion coefficient
D_T	thermophoresis diffusion coefficient
N_B	dimensionless Brownian diffusion
N_T	dimensionless thermophoresis diffusion
Re	Reynolds number
Pr	Prandtl number
Sc	Schmidt number
$\mathbf{W}^{1,3}(\Omega)$, $L_0^2(\Omega)$	the Sobolev space

Greek symbols

ω	rotate speed
ρ_f	density of base fluids
ρ_p	density of nanoparticles
η	relative viscosity coefficient
$\sigma_{\mathbf{u}}$	viscous part of nanofluids
$\sigma_{\mathbf{C}}$	diffusion of nanoparticles in nanofluids
θ	dimensionless temperature
ϕ	dimensionless concentration of nanoparticles
Ω	the computing domain
Γ	boundary of the computing domain
δ	penalty parameter
$\sigma'_{\mathbf{u}}$	dimensionless viscous part of nanofluids
σ_ϕ	dimensionless diffusion of nanoparticles

serial analytical solution for the two-dimensional natural convective boundary-layer flow of a nanofluid past a vertical plate. Hassani et al. [16] investigated the problem of the boundary layer flow of a nanofluid past a stretching sheet by using the homotopy analysis method (HAM). Mustafa et al. [17] also considered analytic solutions for the flow of a nanofluid near a stagnation point toward a stretching surface by using HAM. Hamad and Ferdows [18] studied heat and mass transfer analysis for boundary layer stagnation point flow over a stretching sheet in a porous medium saturated by a nanofluid with internal heat generation/absorption and suction/blowing by using lie group analysis method. Zheng et al. [19] presented research on the flow and radiation heat transfer of a nanofluid over a stretching sheet with a velocity slip and temperature jump in a porous medium by using HAM. Abbasi et al. [20] analyzed the magnetohydrodynamic doubly stratified flow of Maxwell nanofluid in the presence of mixed convection by using HAM. Hatami and Ganji [21] investigated coupled equations of the motion of a particle in a fluid forced vortex by using by using the differential transformation method (DTM) with the Padé approximation and the differential quadrature method (DQM). Hatami and Ganji [22] considered the equation of a particle's motion on a rotating parabolic surface by using multi-step differential transformation method (Ms-DTM). Later, Sheikholeslami and Ganji [23] studied the effects of Brownian motion on the nanofluid flow and heat transfer between parallel plates by using DTM.

The above mentioned investigations [15–23] with that used Buongiorno's model [14], in which Brownian motion and thermodynamics were considered the most important factors affecting nanofluid behavior were restricted to analytical solutions. In the analytical process, some self-similarity transformations should be set up. Because the temperature equation is coupled to the concentration equation in Buongiorno's model, an appropriate similarity transformation was difficult to obtain in actual engineering. Thus, some numerical methods were applied to solve for the flow, heat and mass transfer of nanofluid with Buongiorno's model. Sheikholeslami and Rashidi [24] presented the effects of a space-dependent magnetic field on the free convection of Fe_3O_4-water nanofluid in an enclosure by using the control-volume-based finite element method (CVFEM). Later, Sheikholeslami and Vajracelu [25] investigated nanofluid flow and heat transfer in a cavity with a variable magnetic field by using the same numerical method. Hsiao [26] investigated stagnation electrical magnetohydrodynamic (MHD) nanofluid mixed convection with a slip boundary on a stretching sheet by using an improved finite-difference method. Esfe et al. [27] examined natural convection in a trapezoidal enclosure filled with carbon nanotube-EG-water nanofluid by using the finite volume method and the SIMPLE algorithm. Garoosi et al. [28] presented numerical research on the heat transfer performance of nanofluids in a heat exchanger. Hayat et al. [29] considered a numerical study of the MHD flow of nanofluid owing to a rotating disk with a slip effect by using BVP4C in MATLAB. Recently, Hatami and coworkers [30–36] numerically investigated flow heat and mass transfer of nanofluids in some complex geometric space (such as wavy-wall enclosure, T-shaped cavity, and microchannel heat sink) by using the finite element method (FEM) and the Response Surface Methodology (RSM). Reddy, Chamkha and coworkers [37–41] numerically studied heat and mass transfer analysis of nanofluids under differential cases and conditions (such as vertical plate, inclined plate, vertical cone, chemical reaction, and porous) by using FEM.

Jiang and coworkers [42–43] presented a numerical simulation for the flow and heat transfer of nanofluid based on power-law fluids in a rotating circular groove by using FEM. Lin, Guo, and coworkers [44–47] presented a thermodynamically consistent phase-field model for two-phase flows with thermocapillary effects by using an appropriate variational form and continuous finite element schemes. Zheng et al. [48] analytically and numerically investigated the steady flow and mass transfer of nanofluids with power-law-type base fluids over a free-rotating disk. HAM was applied to solve the ordinary differential equations (ODEs), and the laser speckle method was used to provide images of nanoparticles suspended in power-law fluids in the rotating disk. In their latest research, Li, Lin, and coworkers [49–51] presented the effects of nanoparticle migration on non-Newtonian nanofluids in a channel with multiple heating and cooling regions by using FEM with Freefem++ software.

Motivated by the above mentioned works [42,43,48], we considered in this study, the flow, heat and mass transfer of nanofluids in a rotating circular groove based on Buongiorno's model [14]. Newtonian and non-Newtonian fluids were chosen as base fluids,